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A Novel Coil Configuration to Extend the Motion Range of Lorentz Force Magnetic Levitation Devices for Haptic Interaction

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Abstract— **Lorentz force magnetic levitation devices have been used for fine positioning, compliant assembly, force-reflecting teleoperation, and haptic interaction. The advantages of Lorentz levitation devices compared to motorized linkage and/or cable devices include the lack of friction, hysteresis, and other nonlinearities in actuation dynamics, the simplicity and robustness of a single moving part, and the potential for high closed-loop control bandwidths, a large impedance range, and precise motion. The principal disadvantage of existing Lorentz levitation devices is their motion ranges of 25 mm or less in translation and 20 degrees or less in rotation, which limits their utility in application domains such as haptic interaction. In this paper a novel coil and magnet configuration is presented which extends the possible motion range of Lorentz force magnetic levitation devices to 50 mm and at least 60 degrees, twice the present maximum range in translation and three times the maximum rotation. The motion range of the device design is confirmed through computer-aided design models and the levitation feasibility is shown through magnetic finite element analysis.**

Keywords: haptic interaction, magnetic levitation

I. INTRODUCTION

Surveys of haptic interface devices include exoskeleton devices, encountered linkage and cable devices, and magnetic levitation devices [1] [2]. The parameters of haptic devices and force-reflecting teleoperation masters which are most critical to the user-perceived quality or transparency of the interaction are their impedance range, closed-loop control bandwidths and position resolution [3]. Lorentz force magnetic levitation devices perform well by these measures [4], but their ranges of motion at present are limited to a maximum of 25 mm in translation and 20 degrees in rotation.

The limited motion ranges of existing Lorentz force magnetic levitation devices do not pose a problem in fine positioning or compliant assembly tasks using a remote center of motion when the levitation device is mounted to a larger-scale coarse positioning device, but in haptic interaction the small motion range directly limits the size of the simulated environment which is encountered through the motion of the user's hand. Increasing the motion range of Lorentz levitation devices to 50 mm and over 60 degrees would more closely approximate the kinematic motion range of the human hand and fingers [5] and enables the simulation of a much broader set of common manipulation tasks without the need for scaling or indexing. Examples of manual tasks in which tools are rotated through 60 degrees include turning hexagonal bolt heads and socket screws, keys, faucets, and common knobs and switches. Furthermore, studies have shown that many minimally invasive surgery procedures require instrument orientation ranges of only 60 degrees [6].

The basic principles and a brief background of Lorentz levitation devices are given in the next section. Section III describes the new concept to increase the motion range of Lorentz levitation devices by increasing the size of the active areas of their actuation coils and arranging them in two layers, and Section IV presents two magnet assembly designs based on the new coil configuration. Electromagnetic fine element analysis results are given in Section V and conclusions and a description of current progress are given in Section VI.

II. LORENTZ FORCE MAGNETIC LEVITATION

Lorentz force levitation uses the forces generated from electric currents passing through magnetic fields to levitate a rigid body. Optical position sensing is used for feedback control.

A. Lorentz Levitation Principle

The Lorentz force generated by each coil is as follows:

$$f = \int B \times I \, dl,$$

where B is the magnetic flux density, I is the electrical current, and l is the total length of the wire passing through the field, integrated along its length in the field. A typical actuator is shown schematically in Fig. 1, in which a flat oval racetrack-shaped coil embedded in the levitated body passes through two regions of high magnetic fields to produce a total common force vector in the plane of the coil and perpendicular to both the magnetic fields and the currents passing through them. To levitate a single rigid body, at least 6 actuators must be embedded in the rigid body and arranged in a configuration so that arbitrary vector forces and torques can be produced by the actuators acting in combination.

The advantage of Lorentz forces instead of electromagnetic attraction or repulsion for magnetic levitation is that the forces generated by each actuator are linearly dependent only on the coil current, magnetic field strength, and the total length of the wire passing through the magnetic field. The force generated does not directly depend on position but only on the variation in the magnetic field strength with position as the coil moves through it.

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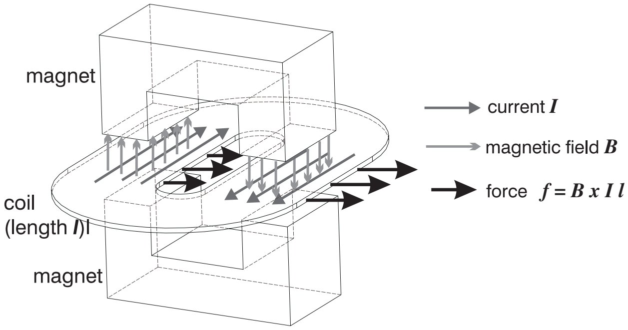

Fig. 1. Typical Lorentz force actuator

B. Previous Lorentz Force Magnetic Levitation Devices

Lorentz force magnetic levitation was first developed at IBM Watson Laboratories where the *Magic Wrist* device was built as a fine-motion robot wrist to be used for compliant assembly operations [7]. A similar device was later developed at the University of British Columbia as a teleoperation master [8]. Other Lorentz force magnetic levitation devices developed at UBC include a teleoperated microsurgery system [9] and a small desktop device for haptic interaction, the *Powermouse* [10]. Another desktop Lorentz levitation device has been developed using laser interferometer position feedback and a different coil and magnet configuration [11].

Another Lorentz levitation haptic interface device was developed at Carnegie Mellon University with significantly larger ranges of motion in translation and rotation than earlier devices [12]. The hemispherical haptic interface device has also been used with a *Magic Wrist* in a dual magnetic levitation master-slave teleoperation system [13]. The larger motion ranges were achieved by embedding the six large actuator coils in a thin, lightweight, hemispherical shell instead of flat panels, and fitting them closely together as shown in Fig. 2.

The original Carnegie Mellon Lorentz levitation device has a position resolution of 10 μm or better, due to its optical position sensing system using LEDs and position sensing photodiodes. The levitated mass using aluminum coils is 580 g. At a control rate of 1300 Hz, the measured control bandwidths were at least 100 Hz for small motions in all directions and approximately 250 Hz for force and torque generation, limited by the fundamental resonant frequency of the coil shell. The maximum stable stiffness of the levitation controller at 1300 Hz is approximately 25.0 N/mm.

New hemispherical Lorentz levitation devices for haptic interaction are currently in fabrication at Carnegie Mellon, based on the previous hemispherical coil and magnet configuration and with improved position sensing, lighter and stiffer materials, and a much faster control system. These devices are expected to show a dramatic improvement in dynamic performance, yet their motion range is similar to the previous device. The ranges of motion of existing Lorentz levitation devices are summarized in Table I.

Fig. 2. Hemispherical magnetic levitation device coils

Device	Translation	Rotation
IBM Magic Wrist	10 mm	6 deg
UBC Teleoperation Master	10 mm	6 deg
UBC Powermouse	6 mm	10 deg
CMU Maglev Haptic Interface	25 mm	15-20 deg
New Univ. of Hawaii Design	50 mm	60 deg

TABLE I
MOTION RANGES OF LORENTZ FORCE MAGNETIC LEVITATION DEVICES

III. NEW MAGNET AND COIL CONFIGURATION

To increase the translation range of a Lorentz levitation device, an existing design can be simply scaled up, but the levitated mass will increase by the scale factor cubed, greatly reducing the maximum control bandwidths and accelerations of the device. To increase the rotation range, however, it is necessary to increase the solid angles spanned by the active areas of each coil. As the coils in the Carnegie Mellon maglev haptic interface already closely fit together in a hemispherical shell, the rotation range for a device with a similar magnet and coil configuration can only be increased by extending the spherical surface, thereby providing a larger area for the coils without increasing the shell radius. Increasing the spherical area in this way produces only incremental increases in the overall device rotation range, however, and the increase in the spherical area reduces the access angle available for the user to reach into the center of the device to grasp the interaction handle.

Another approach to increasing the rotation range for Lorentz levitation devices is to allow the coils to overlap. If the curved, inactive regions of the coils overlap outside of the regions which pass through magnetic fields, then the magnet assemblies do not need to be extensively modified, however the overall increase in rotation range to be had by this approach is marginal. If the active areas of the coils overlap, then the paths of the coil windings in those regions must not be parallel, or the force vectors generated by the overlapping coils will not be independent. The magnet configuration may also need to be modified due to the increased topological complexity of the overlapping regions.

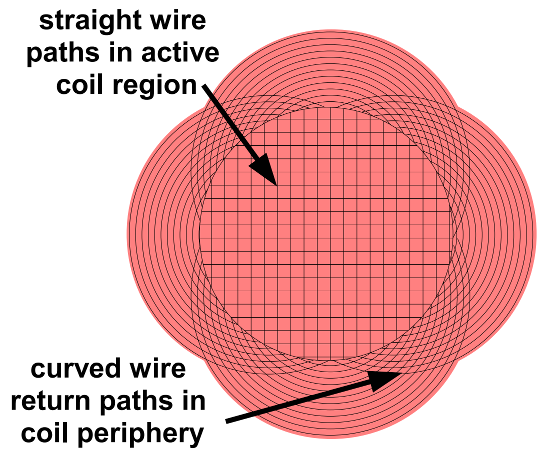

Fig. 3. Double coil winding layers for planar motion

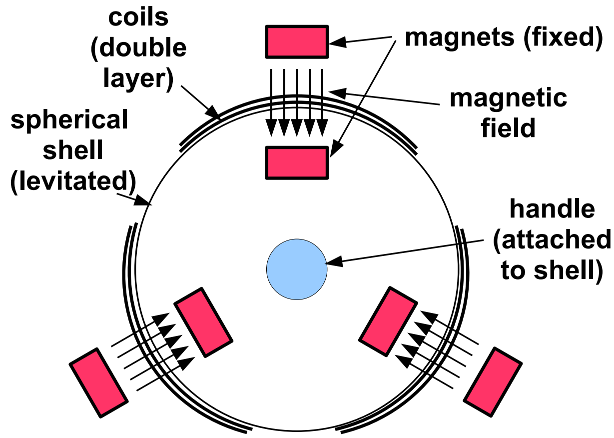

Fig. 4. New coil configuration

To increase the rotation range of the Lorentz levitation devices by a factor greater than two, a novel coil and magnet configuration is proposed: Instead of using oval racetrack-shaped coils, each coil is wound so that the wires are straight and parallel in the center of the coil and follow curved return paths along the outer edges. Each coil therefore has a single large active region in its center, instead of two small active regions in the straight sections on either side of the oval coils. As a result, the active regions of equivalent sized coils are much larger and the coils can be arranged in two layers with the wires through their active regions perpendicular to each other, sharing the same region of magnetic field and able to generate both x and y forces tangent to the coil surface, so that 6 coils on the shell together can generate forces and torques in all directions. Two such coils layered on top of one another at right angles on the spherical shell are shown schematically in Fig. 3.

In the new configuration, each coil has a single active area, and each magnetic field region is shared by two coils. With 6 coils used for levitation and a permanent magnet on each side of each magnetic region, only 6 magnets are necessary as shown in Fig. 4. In previous Lorentz levitation devices, each of the 6 coils has two active areas and each magnetic field region is separate, so a total of 24 permanent magnets are used.

The large size, spherical shape, and unconventional configuration of the actuator coils pose a challenge in fabrication, as they cannot be produced by typical coil winding machines and must be wound by hand. To wind coils in the correct shape, the coils can be wound directly on the outside surface of the spherical shell around pins temporarily attached to the surface. Round wire can be used for the coil windings rather than ribbon wire as used in previous devices. To minimize the area of the curved paths on the periphery of the active area of each coil, the wires can be packed together more densely in these areas, instead of laid flat as in the active areas. This allows the active areas of the coils to be made larger and the coils packed more tightly together, increasing the rotation range of the device. A sample coil wound on a spherical shell by this method is shown in Fig. 5.

Fig. 5. Sample coil winding on spherical surface

IV. MAGNET ASSEMBLY DESIGN CANDIDATES

To achieve high magnetic flux densities in the gaps between the magnets and through the coil surfaces as in Fig. 4, each pair of magnets must be connected by an iron flux path around the coils and through an opening the spherical surface in which the coils are embedded. There must also be an opening in the spherical coil surface and structure of the magnetic flux paths sufficiently large for the user to comfortably reach in to the center of the device to grasp the handle when the levitated body is anywhere within its motion range.

In the first design presented below, the iron magnetic flux paths and the hand of the user both pass through a single large opening in the top of the spherical coil shell. In the second design, the user's hand passes through a large opening in the top of the spherical surface, and the magnetic flux paths pass through a smaller opening in the bottom of the sphere. The radius of the hemispherical shell is set to 115 mm to comfortably enclose the levitated handle, the hand of the user, and the inner set of permanent magnets throughout the motion range of the levitatated body in translation and rotation, yet minimize the mass and moments of inertia of the levitated body.

A. Single Opening Design

This first design, in which the magnetic flux paths and the wrist of the user pass through a common opening in the spherical shell, is shown in Fig. 6. The principal advantage of this design is the large continuous spherical area available to place the actuator coil pairs. In this design, the iron return paths for the magnetic flux pass over the top edges of the levitated shell. These iron flux paths must follow large curved projections around the edges of the coils to accomodate the maximum rotation and translation limits of the levitated shell from its center position.

The iron magnetic flux paths are independent and separate for each pair of magnets. To improve the access of the user's hand and wrist from the front of the device to grasp the handle fixed to the center of the levitated shell, two of the flux paths are rotated away from each other by 30 degrees around the central axes of their magnet pairs and the third flux path is vertical. This geometry also allows the coil shell to be removed without disassembling the magnet assemblies.

The preliminary design in Fig. 6 has a rotation range of 60 degrees and a translation range of 50 mm. The active region of each coil spans an angle of 75 degrees to account for the diameter of the magnet pairs and their magnetic fields. The total angular span of each coil pair is approximately 90 degrees including the curved winding return paths around the periphery of the active areas. These areas may overlap between neighboring coil pairs as the magnetic fields do not pass through them.

The rotation range of this design could be extended to as much as 75 degrees by expanding the coil areas further, but this would require also extending the curved iron flux paths accordingly and reducing the user hand access to grasp the handle at the center.

Some advantages of this design are that the magnetic assemblies and the levitated coil shell are not difficult to fabricate and assemble, and a large unoccupied volume directly underneath the levitated shell is available to install position sensors to track the motions of LEDs attached to the levitated shell. One possible concern of the design is that the user's hand may pass in close proximity to high magnetic field areas: No intrinsic hazards to humans have been found due to high magnetic fields and the United States Food and Drug Administration has declared magnets in health therapy as "not harmful", but any ferrous metals worn on the fingers or wrist of the user could cause problems. Also an additional rigid frame is necessary in the device to support and fix the magnet assemblies in place.

B. Double Opening Design

In the second device design, the iron magnetic flux paths between the magnet pairs all pass through an opening in the bottom of the coil shell, and the hand and wrist of the user pass through the top of the shell to grasp the attached handle. The three iron magnetic flux paths intersect to pass through the coil shell, forming a single magnet assembly. A preliminary model is shown in Fig. 7, with the same 90 degree angle total coil sizes and 60 degrees and 50 mm motion ranges as the single opening design. This design may also be modified to increase its rotation range somewhat, but the size of the top opening of the coil shell would need to be reduced, forcing the user to reach further down into the shell to grasp the handle at the center.

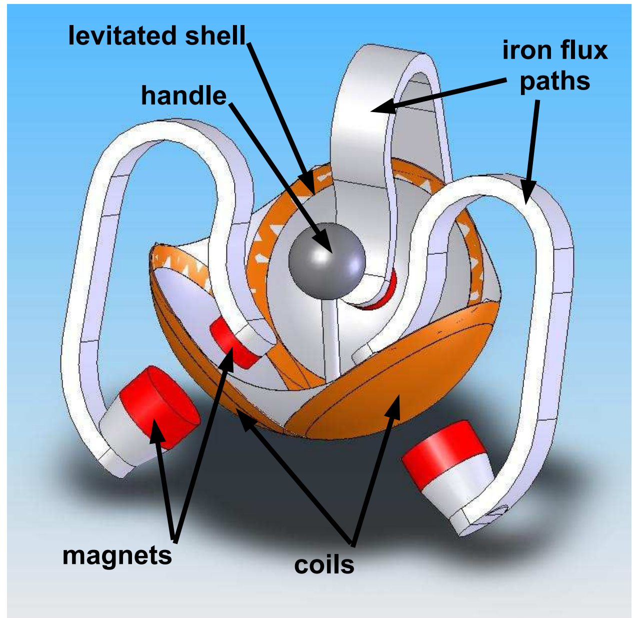

Fig. 6. Single opening design

An advantage to this design is that the top opening of shell is free from any obstructions, as the iron magnetic flux paths all pass underneath the shell. The iron flux paths are longer and more complex in this design but generally farther removed from the user's hand, so there is less of a concern that ferrous rings or watches could be attracted to the iron pieces. The three magnetic flux paths are combined in a single assembly so no additional structure is required to support them.

Three struts are used to attach the handle to the coil shell and provide additional structural rigidity due to the opening in the bottom of the shell. These three struts may get in the way of the user's fingers while grasping the handle. However, they provide an advantage also in that the return paths for the wires in three of the coils can be passed through these struts instead of occupying additional area on the outer surface of the coil shell. Open areas are available between the iron flux paths on the sides of the levitated shell for three separate optical position sensors.

V. MAGNETIC SUBASSEMBLY DESIGN

An FEA software package[1] was used to refine the dimensions of the magnets and flux paths for the designs described

[1] ANSYS Emag, Canonsburgh PA

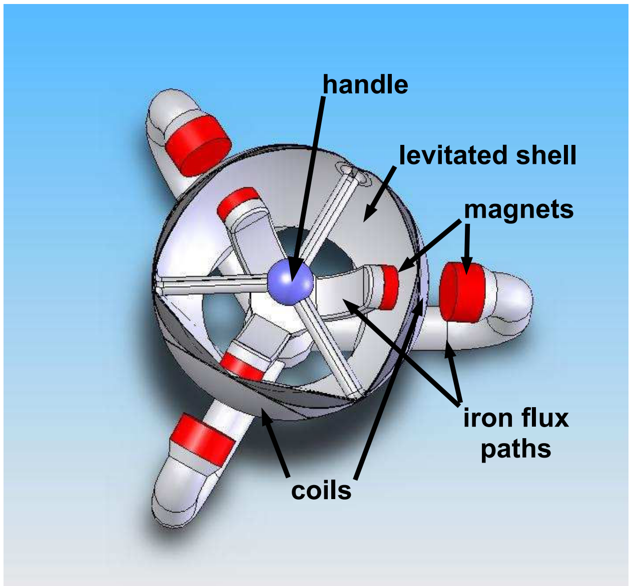

Fig. 7. Double opening design

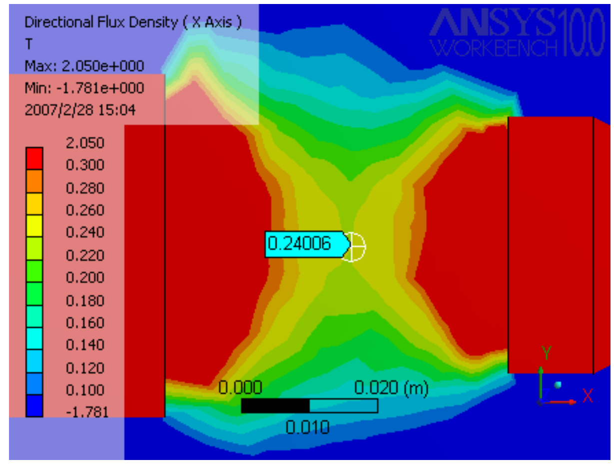

Fig. 8. Finite element analysis flux density in magnetic gap

Outer magnet thickness	Inner magnet diameter	Magnetic flux density at center
12.5 mm	25 mm	0.1823 T
25 mm	25 mm	0.2032 T
37.5 mm	25 mm	0.2256 T
50 mm	25 mm	0.2304 T
12.5 mm	37.5 mm	0.2185 T
25 mm	37.5 mm	0.2401 T
37.5 mm	37.5 mm	0.2521 T
50 mm	37.5 mm	0.2610 T

TABLE II

MAGNETIC FLUX DENSITY IN CENTER OF MAGNET GAPS

in the previous section and verify that the magnetic fields between the magnet pairs are sufficiently high that sufficient forces for levitation and motion control can be generated without overheating the coils.

Neodymium-iron-boron [NdFeB] permanent magnet materials with a magnetic energy product of 50 MGOe are commonly available. Due to their very high intrinsic magnetic fields, flux density concentrations can surpass 1.5 T as the flux paths change direction with small radii of curvatures. To minimize the likelihood of magnetic saturation effects, pure iron with a saturation level of approximately 2.0 T is to be used in the magnetic flux paths.

A. *Magnetic Flux Density*

To produce Lorentz forces sufficient for levitation, motion control, and responsive force feedback, a magnetic flux density of at least approximately 0.25 T is desired along the central axis of each magnetic gap. FEA modeling was performed for various combinations of magnet dimensions, as it was found that the magnetic field produced across a 50 mm gap depends primarily on the magnet dimensions and only to a minor degree on the shape of the iron flux return path, provided that magnetic saturation effects in the iron are not significant. Additional magnets along the magnetic flux paths also have negligible effects on gap fields. 50 MGOe NdFeB disk magnets are generally commercially available in diameter and thickness increments of 12.5 mm, or approximately 0.5 inch, so FEA modeling was performed using these dimension increments.

FEA modeling results show that a pair of 25 mm diameter magnets, 50 mm thick, with a 25 mm diameter pure iron flux path and separated by 50 mm, produce a magnetic field across the gap which decreases to a minimum of 0.15 T along the central axis between the magnet faces. This field strength does not meet the requirement above as it would require denser coil windings and higher actuation currents for levitation than anticipated.

As 25 mm diameter magnets were not sufficient to produce the desired magnetic field strength, FEA models were solved for magnets with 37.5 mm and 50.0 mm diameters. The magnet on the inside of the coil shell was limited to a thickness of 12.5 mm to avoid interference with the hand of the user, and a diameter of 50 mm was taken for the outer magnet. The magnet diameters were not increased further because larger diameter magnets reduce the rotation range as the wider magnetic field regions reach the boundaries of the coil active regions sooner and begin to interfere with the currents in the wire return paths of the coils.

The solution results from varying the outer magnet thickness and the inner magnet diameter are listed in Table II. The outer magnet thickness of 25 mm and inner magnet diameter of 37.5 mm were selected for the magnetic assembly design; a slice of the FEA solution results through the magnet gap is shown in Fig. 8. Although the minimum magnetic field strength in the center of the gap is 0.24 T and less than the targeted value of 0.25 T, further increases in magnet dimensions produce only very small increases in this minimum value. Regarding the magnet diameters, it appears that diameters comparable to the gap width are a reasonable design choice in general to maintain magnetic field strengths across the gap.

B. Actuator Force Generation

A coil winding body model with a defined electric current can be added to the magnetic FEA model shown in Fig. 8 in the gap between the magnet faces to find the actuation forces produced by the interaction of the coil current and the magnetic field. Given a winding density of 4 wires per mm corresponding to 30 AWG gauge wire, a 1.0 A current in the coil at the center of the gap produces a force of 7.0 N in the FEA model, sufficient for levitation and accelerations of several g provided that the levitated mass is minimized. The forces generated will be somewhat greater as the coil moves closer to either magnet face, as the fringing of the magnetic flux increases with the distance from the magnet faces. The direction of the generated force also changes with the orientation of the coil. These variations in the Lorentz force generated from a constant coil current will be compensated by the levitation controller.

VI. CONCLUSIONS AND FUTURE WORKS

A. Conclusions

The preliminary kinematic analysis of the two device designs shown demonstrate the feasibility of Lorentz levitation with rotation ranges of 60 degrees or more in all directions. Electromagnetic finite element analysis shows that the actuation forces achievable with the new coil and magnet configurations are equivalent to previous designs.

The greatly increased motion range of the new device designs provided by the new coil shapes and two-layer configuration will make possible haptic interaction and force-reflecting teleoperation with a much larger range of application environments and simulated tasks as the larger motion range more closely conforms to the motion range of tool handles held by the fingers of users. A 60 degree rotation range can encompass typical task simulations such as turning doorknobs and keys, minimally invasive surgery, and turning hexagonal bolts and sockets with handheld tools. The new design also retains the high impedance range, low inertia, high control bandwidths, and high position resolution of previous hemispherical Lorentz magnetic levitation devices.

B. Future Works in Progress

The final design to be fabricated will be selected from the preliminary designs by building mockups of the two described designs pictured in Figs. 6 and 7 and evaluating their ergonomic qualities to determine which levitated body is more comfortable to grasp and manipulate without contacting the fixed iron magnetic flux paths or the rim of the levitated shell with the fingers. Fabrication of the selected levitation device design is to be completed during summer 2007, to be followed by individual and collective testing of the Lorentz force actuators and initial levitation tests.

The position sensing system necessary to provide real-time position and orientation feedback for levitation will be initially provided by a commercial high-speed rigid-body motion tracker[2] using infrared LEDs attached to the levitated shell, to be replaced by an optical position sensing subsystem similar to those used in previous devices [12] and developed in our laboratory specifically to fit the range of motion of the new device.

The levitation control software will be refined to provide consistent force and torque generation across the complete motion range of device, accounting for variations in magnetic field and the positions and orientations of each individual coil. Electromagnetic finite element analysis will be used to calculate the variations in forces, to be confirmed by measurements taken with a 6-axis force-torque sensor [3].

As the performance of the fabricated device is improved, detailed haptic environments will be programmed such as minimally invasive surgical procedures, mechanical assemblies, and haptic displays of dynamic multidimensional data such as fluid flow. The new motion capabilities of the device will correspondingly expand the range of research which can be undertaken in haptic interaction, manipulation, and perception at high bandwidths and position resolutions.

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[2]OptoTrak Certus, Northern Digital Inc.

[3]Mini40, ATI Industrial Automation